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Innovative Streambank Protection in an Urban Setting, Accotink Creek, VA

by David L. Derrick and Meg M. Jonas

PURPOSE: The goal of this Coastal and Hydraulics Engineering Technical Note (CHETN) is to present the planning, design, construction and 10-year performance evaluation of a comprehensive streambank protection project constructed in an urban watershed (Figure 1). This project used a combination of bendway weirs and longitudinal peaked stone toe protection (LPSTP or stone toe) to protect bridge abutments, stabilize an eroding bank line, and initiate floodplain formation. The project features were adjusted to site conditions to minimize environmental impacts. The project is a good example of the use of bendway weirs and stone toe in combination to provide effective, economical, and environmentally sound streambank protection.

BACKGROUND: The project site is located on Accotink Creek in south central Fairfax County, VA, and it provides protection for Panther Bridge, Fort Belvoir. The U.S Army Engineer Research and Development Center's Coastal and Hydraulic Laboratory (ERDC-CHL) was tasked with devising a conceptual design to stabilize erosion to bridge abutments, an eroding bend and a straight reach upstream of a two-lane highway bridge on Accotink Creek. The two-lane road is called Farrar Road and is the major thoroughfare to the installation's airport. Planning for the project started in 1996, construction was performed in September 1997, and it has been reviewed periodically (most recently in December 2008). ERDC-CHL provided construction oversight, and taught a stream stabilization/restoration class during the project construction window.

SITE HISTORY AND SPECIFICS: The project site is a section of Accotink Creek immediately upstream of a two-lane highway bridge (Panther Bridge, named for the Army battalion that built it) for Farrar Road. This reach is located near the downstream end of the drainage basin, approximately 1-1/2 miles upstream of the tidal influence. Accotink Creek drains 51.1 square miles of Fairfax County, a highly developed urbanized area of northern Virginia, where most of the watershed has levels of imperviousness exceeding 25 percent (Fairfax County Department of Public Works and Environmental Services 2001).

In this reach, the stream has a gravel-cobble-sand bed, and pool-riffle regime, flowing in an alluvial valley with a wide, relatively intact, forested climax community riparian corridor. Channel slope through the project is less than 1 percent; stream width at low flow varies from 30 to 50 ft. Upstream of the project reach the stream is straight for approximately 300 ft, providing good entrance conditions to the project area. Approximately 300 ft upstream of the bridge the stream flow impinges into a tall, fairly resistant bluff, before crossing the channel and eroding the right descending bank for a considerable distance downstream to the right abutment of Panther Bridge (Figure 2). This erosion threatened to flank (erode behind) the right abutment of

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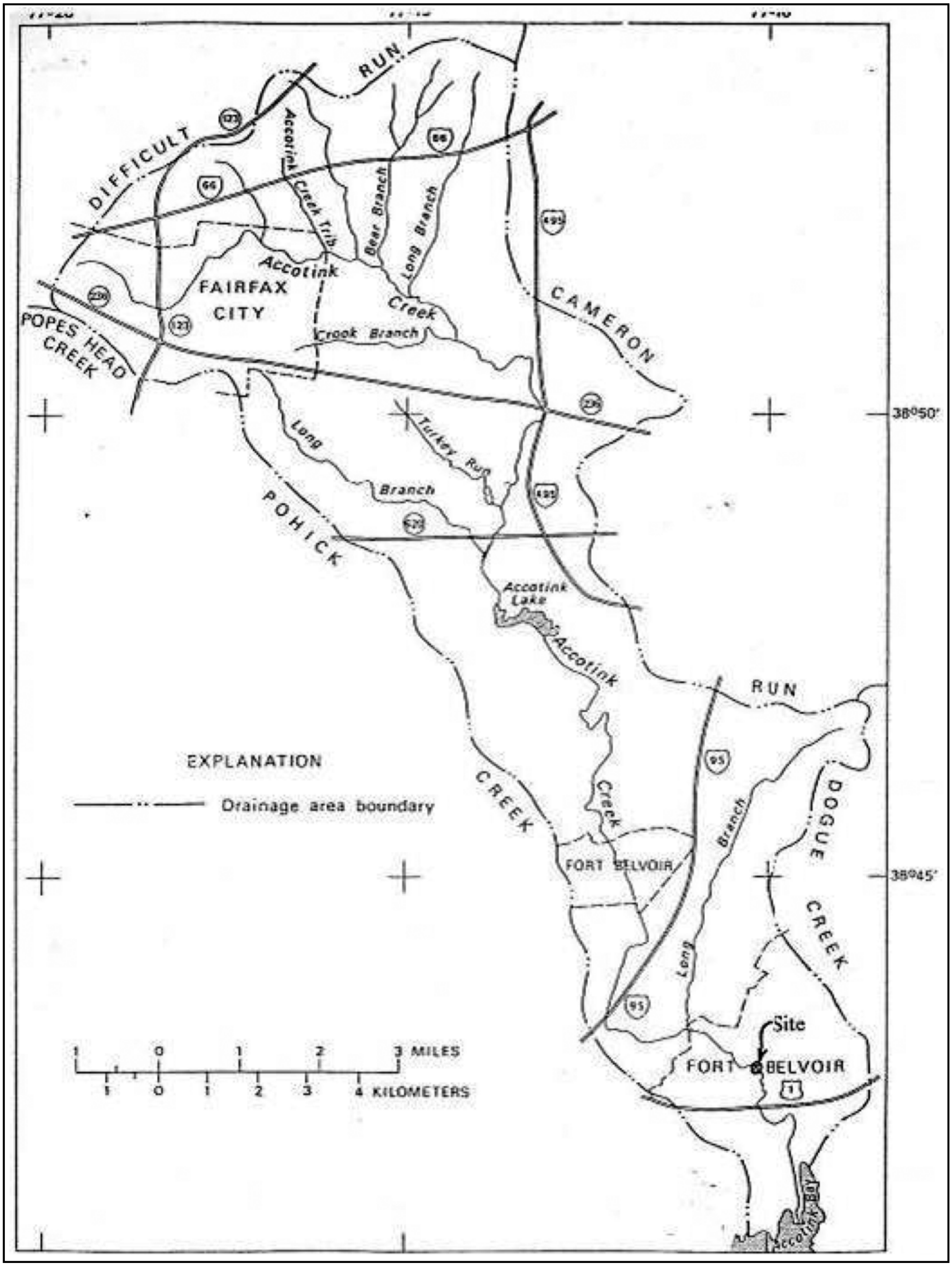

Figure 1. Map of Accotink Creek watershed.

the bridge. The degree of erosion was increased by currents aimed toward the right bank by a broad midchannel bar, formed by backwater from the undersized bridge opening downstream (Figure 3). (The designations "right" and "left" will be used throughout with the observer looking downstream.)

Figure 2. Aerial photograph of project area with project limits, Accotink Creek at Panther Bridge.

DESIGN GOALS: Project goals were to provide economical, environmentally compatible, and hydraulically effective long-term protection for Panther Bridge, while at the same time reducing erosion and improving streamflow within the project limits. The combination of bendway weirs and LPSTP in the plan presented herein is designed to stabilize the banks and improve flow characteristics through the bend and straight section of the stream upstream of the bridge. Specifically, the bendway weir and LPSTP combination forms an energy management system designed to realign and reduce near-field outer bank velocities, and realign the thalweg to a position off the steam ends of the weirs through the bend upstream of the bridge. The bendway weirs will dissipate stream energy within the project and reduce adverse effects downstream of the project. This combination of methods has proven to be more hydraulically and environmentally effective than a single stand-alone treatment.

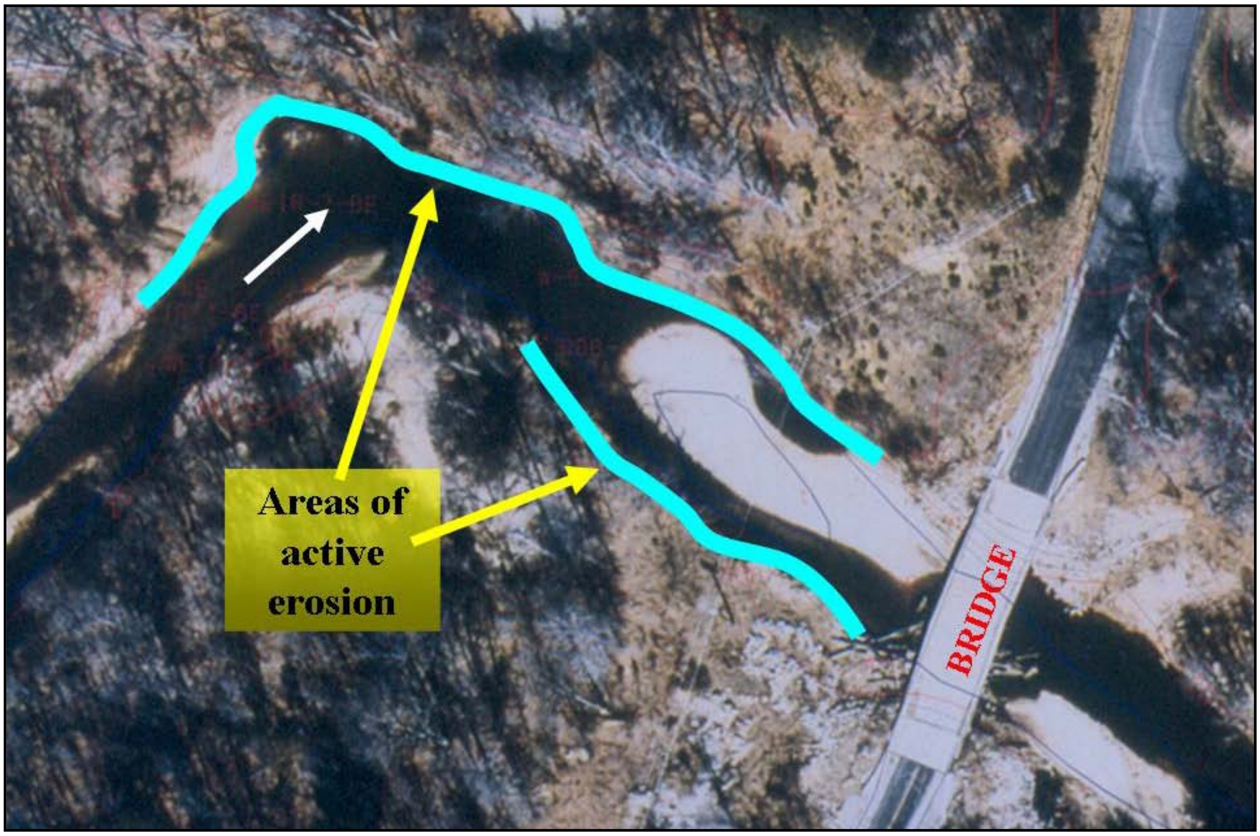

Figure 3. Active bank erosion areas and current flow within the Accotink Creek project area.

CONCEPTUAL DESCRIPTIONS OF STABILIZATION METHODS USED: The LPSTP is a low-elevation continuous stone revetment placed longitudinally at, or slightly streamward of, the toe of the eroding bank. Cross-section is triangular. The LPSTP does not necessarily follow the toe exactly, but can be placed to form a "smoothed" alignment through the bend. LPSTP can also be placed away from the eroding bank to create a new "false bank line" in an improved alignment. A false bank line was used to create a "smoothed" alignment in the bend for this project (Figure 4).

Amount of stone used depends both on depth of scour at the toe and estimated stream forces (impinging flow) on the bank. Amount is normally given as either amount of stone per linear foot of LPSTP (for example, 2 tons per lin ft) or construction of the LPSTP to a certain elevation.

LPSTP must be keyed deeply into the bank at both the upstream and downstream ends and must employ tie-backs and keys along its length.

Tie-backs are short dikes connecting the LPSTP to the bank at regular intervals (75- to 100-ft spacing is typical on small to medium sized streams). The tie-back is then keyed into the bank.

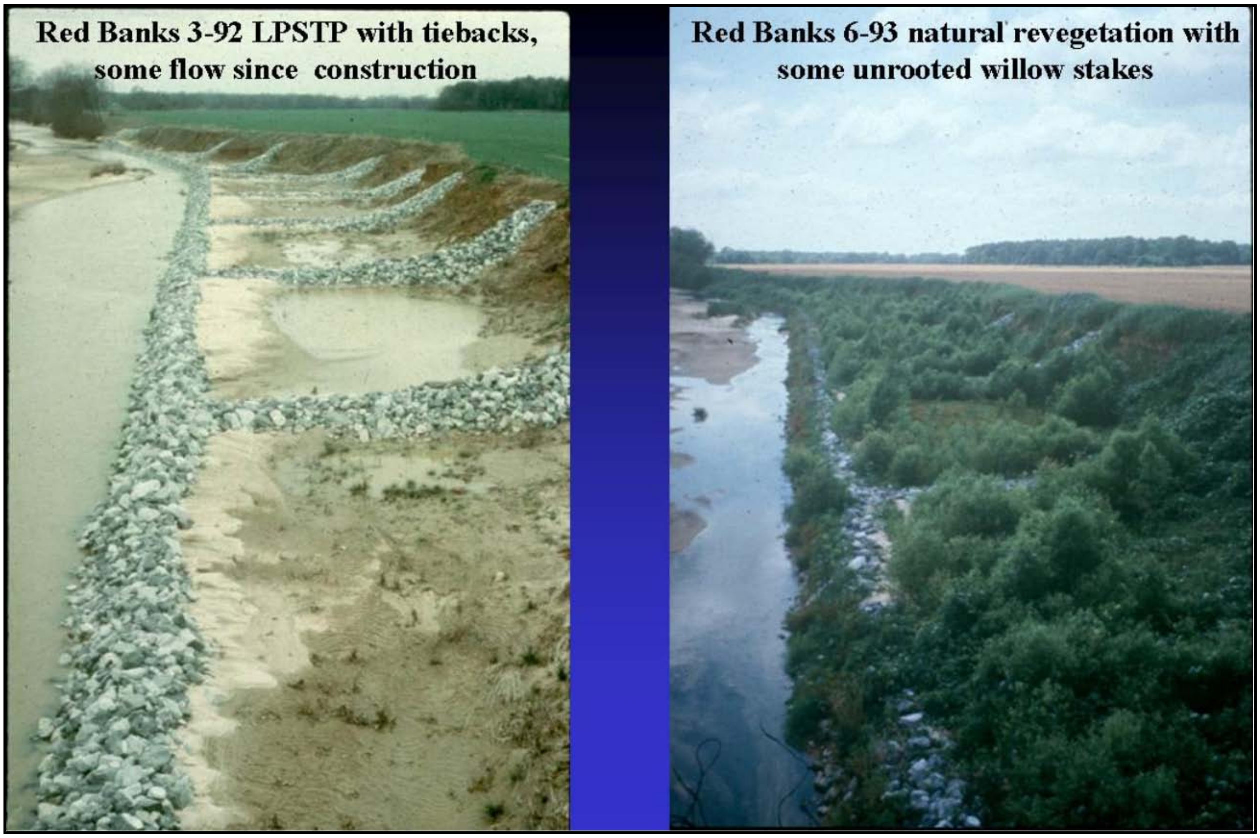

Figure 4. Longitudinal peaked stone toe protection built to provide a false bank line.

The LPSTP resists the erosive flow of the stream and stabilizes the toe of the bank. The "smoothed" longitudinal alignment results in improved streamflow near the toe. Success depends on the ability of stone to self-adjust (launch) into the scour hole. The weight of the stone (loading of toe) can resist some geotechnical bank failure. Alluvium and upslope failed material is captured on the bank side of the structure. Bank grading, sloping, or reshaping might not be needed and was not employed in this project. LPSTP is a good method to use where continuous bank protection is needed, and is well suited for small radius and/or high degree of curvature (horseshoe type) bends. LPSTP also works well in zoned and blended configurations (with bioengineering mid to upper bank protection or bendway weirs and bioengineering). However, LPSTP only provides toe protection; it can be overtopped during high stage events and some scouring of the bank may occur (Figure 5).

Stone bendway weirs are upstream angled low-elevation sills. When submerged, water flowing over the crest of the weir is redirected at an angle perpendicular to the longitudinal axis of the weir. When the weirs are angled upstream, flow is directed away from the outer bank and toward the inner portion of the bend. Due to the form roughness of the weirs, velocities within the weir field are typically reduced by approximately half (Derrick 2009). The stream's strong secondary currents (helical flow) in the bend are broken up. A set of weirs is designed to act as a system to capture, control, and redirect current directions and velocities through the bend and well into the downstream crossing. The last weir in the system can aim flow (and the channel thalweg) where

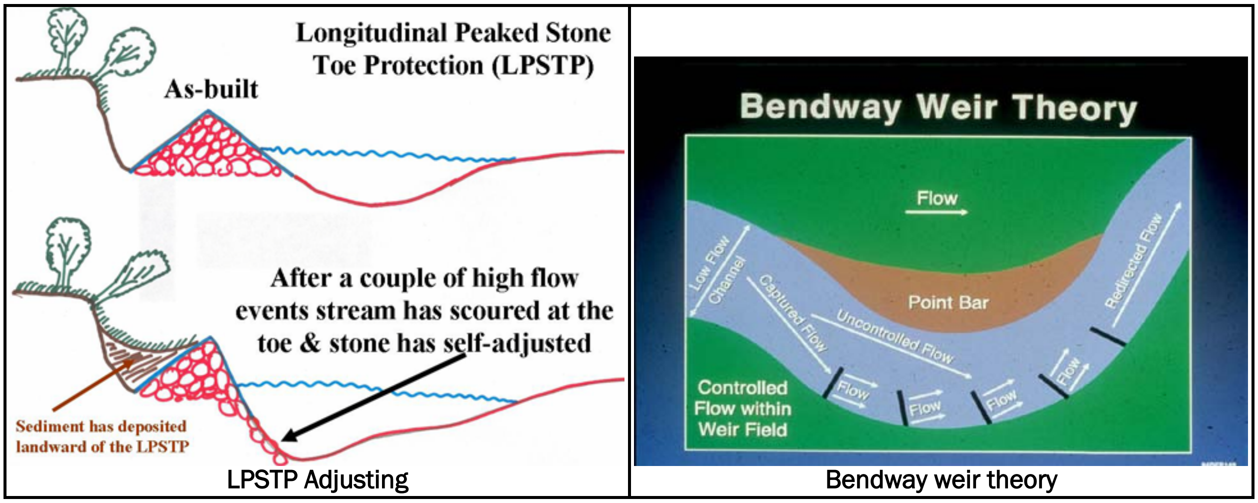

Figure 5. Bendway weir theory.

it is required, based on project performance goals. Both prototype and model results (Derrick et al. 1994) indicate that construction of a series of bendway weirs in a bend results in the following hydraulic improvements: deposition occurs at the toe of the bank on the outside of the bend in the upper section of the bend thus increasing bank stability, surface-water velocities are more uniform across any cross section (slower on outside of bend, faster on inside of bend when compared to a similar bend without bendway weirs), flow patterns in the bends are generally parallel with the banks (flow not concentrated on the outer bank of the bend), and the thalweg of the channel is moved from the toe of the eroding outer bank out to the stream ends of the weirs. Advantages of bendway weirs include the following: flow can be redirected (even downstream of the weir field), weirs work well under high-flow, high-energy conditions, and aquatic habitat diversity and complexity of the reach is improved. Weirs function well with other bank protection methods, and costs are competitive, or lower (considerably in some cases) than traditional methods.

FLOW ISSUES WITH BRIDGE: Panther Bridge was constructed at a low elevation, and will not pass the 2-year flood (Figure 6). The lowest road elevation is 24.7, while the minimum water surface elevation for the discharge associated with the 2-year storm is 27.6, which results in 2.9 ft of flooding of the road (Sheladia Associates 1996).

The bottom of the bridge girders is typically only 50 in. above the base flow water surface elevation. Due to the undersized bridge opening and the low elevation of the bridge span, maintenance removal of large woody debris has been an ongoing problem. However, since project completion, less debris removal has been required from the bridge abutment (Hudson 2009). This is probably due to improved alignment of the main current through the bridge opening.

The bridge has also caused backwater effects which have resulted in the formation of a large gravel-cobble midchannel bar immediately upstream.

Figure 6. Undersized bridge opening, Panther Bridge at downstream end of project (branch stuck up under bridge).

THE PLAN

Overview. The project site includes the 90-deg right bend and straight reach of Accotink Creek immediately upstream of Panther Bridge. The major components of the plan consisted of 250 lin ft of LPSTP along the left descending bank of the bend and downstream of the bend, a system of five bendway weirs tied to the left bank LPSTP in the bend, and LPSTP along the right bank extending from the lower end of the point bar of the bend to the upstream right abutment of the bridge (Figure 7). All keys, bendway weirs, and LPSTP were constructed of Virginia DOT Class II stone (150-500 lb., well-graded, self-adjusting stone). A geotextile or granular filter was not needed for either the bendway weirs or the LPSTP as the stream's gravel substrate acts as a natural granular filter blanket.

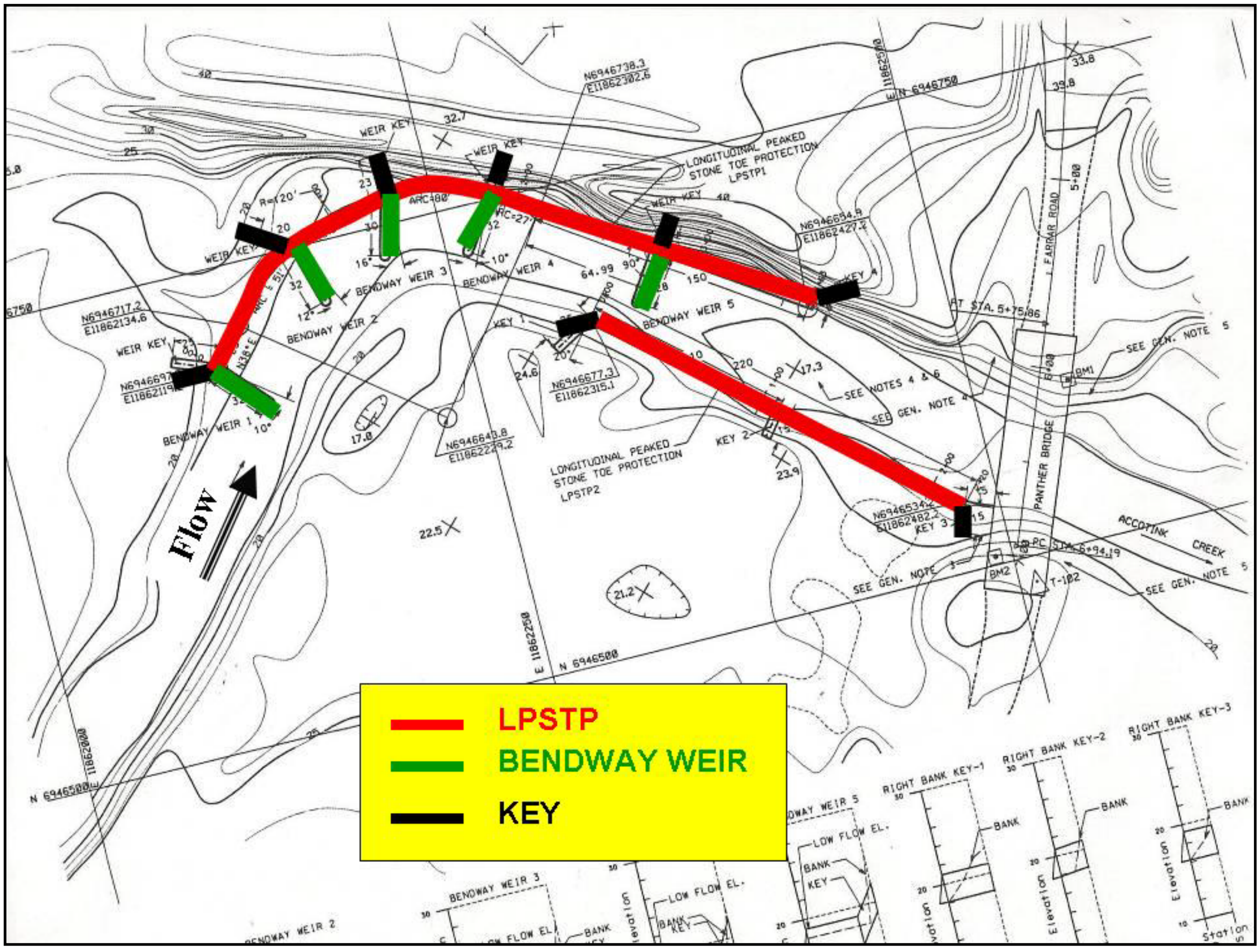

Figure 7. The stabilization plan.

Left Bank LPSTP. All LPSTP in this project was built level-crested at an elevation 3 ft above the typical low-flow water-surface elevation. The upstream key for the LPSTP is 25 ft long, 3 ft deep, and 5 ft wide. This also serves as the key for bendway weir 1. The left bank LPSTP begins at weir 1 and ends 82 ft downstream of the intersection of the LPSTP and the bank end of bendway weir 5. The bend radius of the LPSTP is 120 ft with an arc angle of 90 deg. The straight sections of the left bank LPSTP upstream and downstream of the curved bend section were 25 ft and 150 ft, respectively. Side slopes of the LPSTP are the angle of repose of the stone. The LPSTP on the left descending bank was keyed at intervals into the outer bank. These keys also serve as keys for the bendway weirs and are described in the following section. The upstream end and downstream end stone keys were 25 ft long, 3 ft deep, and 5 ft wide with soil choke. These keys are angled 30 deg to flow.

Stone Bendway Weirs. All bendway weirs were built level-crested to a height equal to 1 ft above the base flow (typical low water) water-surface elevation at the location of the weir. A minimum section (vertical thickness) of stone of 3 ft was maintained for all bendway weirs and weir keys. To maintain the 3-ft section, some excavation of the streambed was performed at some weirs. In the case of weir 1 (located in the shallow riffle at the upstream portion of the project bend) approximately 2 ft of excavation was performed along the entire length of the weir

to maintain the 3-ft section. A crest width of 5 ft was maintained for all weirs and weir keys. Side and end slopes of weirs were the angle of repose of the stone (approximately 1.5 horizontal to 1 vertical). Angles of weirs 1 and 5 are relative to a line perpendicular to the LPSTP intersecting the bank end of the weir. Angles of weirs 2, 3, and 4 are relative to a line drawn from the bank end of the weir to the center of the arc. Keys on weirs 3, 4, and 5 were 5 ft wide, were dug 5 ft into the bluff, with the crest 5 ft above the low-flow water-surface elevation (Figures 8-10). A minimum 3-ft section was maintained in the transition from the key to the weir. Table 1 lists the bendway weir dimensions and spacing.

Figure 8. Looking downstream at impinging flow into tall bank area, left descending bank, 25 October 1996.

Midchannel Bar Upstream of Panther Bridge. A portion of gravel and cobble was removed from the upper end of the midchannel bar located upstream of the bridge. This material was used on-site for a number of purposes, including filling streambank and overbank voids on the left bank upstream of the bridge, and covering some broken concrete rubble (urbanite) on the right bank floodplain. Gravel and cobbles from the bar were also used as fill material between the left bank LPSTP and the left bank, and the right bank LPSTP and its bank.

Figure 9. Normal flow, looking downstream at LPSTP and weirs 2 and 3, September 1997 (during construction).

Figure 10. Looking downstream at bendway weirs 1-3, 17 May 2000 (2.75 years after construction).

Table 1. Bendway weir design specifications for the project bend upstream of panther bridge (radius = 120 ft, degree of curvature = 90).

Weir	Height	Angle (deg u/s)	Length (ft)	Key Length (ft)	Spacing Between Weirs (ft)
Weir 1	BFWSE+1ft	10	32	25	
					76
Weir 2	BFWSE+1ft	12	32	20	
					55
Weir 3	BFWSE+1ft	16	30	23	
					60
Weir 4	BFWSE+1ft	10	32	8	
					92
Weir 5	BFWSE+1ft	0	28	11	

Notes:
BFWSE means Base Flow Water-Surface Elevation.
Spacing is measured from bank end of weir to bank end of weir.

Right Bank LPSTP. The upstream end of the LPSTP on the right descending bank was keyed at a 30-deg angle to flow, 25 ft into the depositional point bar material (on the inner bank of the project bend). It was oriented at a 30-deg angle to flow. The stone key section was 3 ft deep and 5 ft wide with a soil choke. To avoid damaging trees in this area, the keyway was placed between existing trees. This LPSTP was built to a height 3 ft above the typical low-flow water-surface elevation. The second key for the right bank LPSTP is located 110 ft from the upstream end of the LPSTP and the third key is located immediately upstream of the bridge. Both the second and third keys were constructed 5 ft wide, with a section depth of 3 ft, and oriented perpendicular to the LPSTP into the bank a distance of 15 ft. Gravel-cobble bar material was used for fill between the right bank LPSTP and the bank.

Overbank Areas Upstream of Bridge. Excess concrete and asphalt rubble on the right overbank upstream of the bridge was removed and properly disposed of. This material could not be used for anything on-site due to size, shape, and the large amount of asphalt mixed with the concrete.

Upstream of the left abutment, the existing broken concrete was pulled into a straight alignment with the abutment and the upstream bluff. This concrete was compacted with the bucket of the track hoe and gravel and cobble from the midchannel bar used to fill voids. This bank was covered with topsoil and seeded.

Downstream of Bridge. Existing broken concrete rubble on both left and right banks and overbank areas downstream of the bridge was left in place. The rubble was compacted, stream gravel added to fill voids, then covered with topsoil and seeded. Both the left and right streambanks for a distance of 80 ft downstream of the bridge were shaped, voids filled using stream gravel, and seeded.

PROJECT CONSTRUCTION SEPTEMBER 1997: All in-stream stone construction work was completed in 4 working days, 8-11 September 1997, with final inspection on 12 September 1997.

Access for construction equipment in the bend was limited to the right bank point bar and from within-stream. Working from the left bank in the bend was avoided due to the wetland areas in the upper section of that bend. Haul roads were constructed with the least impact on the surrounding area. One haul road was constructed on an existing pathway and was left as an inspection route.

Stone was staged (temporarily stored) on the point bar for easy access and short haul distance. It was anticipated this area would be modified to a degree by flow around the bendway weirs.

Construction proceeded from upstream to downstream. The upstream key for the left bank LPSTP was constructed first. A section of LPSTP would be constructed, then a key, then one of the bendway weirs, then more LPSTP, then another key, then another weir.

The project reach between bendway weirs 3 and 5 contained one of the deepest, relatively stable, scour holes in the entire creek. This deep water provides good aquatic habitat. To prevent excessive filling of the deep scour hole, a ledge was cut in the clay on which to place the left bank LPSTP. The location of the bendway weirs was modified slightly to adapt the design to site conditions and minimize the impact on this aquatic feature.

The right bank LPSTP was constructed last and was designed to reduce active bank erosion, to save seven mature trees from becoming undermined and falling into the creek, and to protect the right abutment to the bridge. However, tree roots exposed by erosion turn into branches (stemwood). These former roots will die if they are covered with soil and smothered. Therefore, the backfill between the LPSTP and the bank in the area of the roots consisted of loose stone that still provided air to the former roots. The final construction actions consisted of reshaping the bank, placing backfill, and seeding areas both upstream and downstream of the bridge.

During construction, an unanticipated sudden release of impounded upstream water resulted in a high-water event that within 5 min overtopped the bendway weirs and within 10 min, overtopped the left bank LPSTP. The high water showed how the various in-stream structures will work. Even though only three of the five bendway weirs were in place, and although velocities were not measured, visual observations of the project showed current velocities were slowed on the outer section of the bend and the thalweg was redirected to an alignment off the ends of the bendway weirs. The project seemed to be operating as designed.

PROJECT COSTS: Project costs are unknown. This project was a small section of a large contract and costs were not broken out. Construction items included riprap and placement. The use of stone toe and bendway weirs minimized costs since grading and clearing of streambanks was not required. Vegetation was not included, as the site was allowed to revegetate naturally, which also resulted in cost savings. Areas immediately adjacent to the bridge and roadway were seeded with grass.

STREAM FLOWS AND HYDROLOGY SINCE PROJECT CONSTRUCTION: Peak discharges at Panther Bridge were computed by Sheladia Associates, Inc. (Sheladia 1996) and are shown in Table 2 along with discharge values computed for points upstream and downstream of the project site (Soule 1977; KCI Technologies 1995). The drainage area at the project site is 50.78 square miles (KCI Technologies 1995). Table 2 provides peak discharge at Panther Bridge,

at a section approximately 5,500 ft upstream of Panther Bridge obtained from the U.S. Geological Survey (USGS) report, and at a section approximately 10,000 ft downstream of Panther Bridge obtained from the KCI report.

Table 2. Accotink Creek flow data.

Analysis	Peak Discharge (Cubic Feet Per Second)				
	2-Year	10 Year	25 Year	50-Year	100-Year
USGS (5,500 ft upstream of Panther Road Bridge)	*	*	13,400	16,700	20,000
SHELADIA (@ Panther Br.)	5,880	11,184	14,827	18,214	21,410
KCI (10,000 ft downstream of Panther Road Bridge)	6,068	11,542	15,301	18,797	22,095

* Values not provided.
From Sheladia Associates, Inc. (1996).

The USGS maintains a gage on Accotink Creek near Annandale, VA (number 01654000). This gage is upstream of the project and also upstream of Lake Accotink, which has no storage. The link is *http://waterdata.usgs.gov/va/nwis/uv?01654000*. The drainage area at the gage is 23.9 square miles. The gage has been operated continuously since 1947.

The USGS gage record indicates that multiple flood events have occurred since the streambank protection project was constructed in 1997. The flood event associated with Hurricane Hanna on 6 September 2008 was the flood of record for the gage, with a stage of 16.26 ft and a flow rate of 12,600 cfs. From 1997 to 2006 there were 11 events that peaked over 2,000 cfs with seven of those events peaking over 4,000 cfs. These peak discharges are listed in Table 3, and a graph of the peak discharges at the gage site is included as Figure 11.

Table 3. Flood peaks for time frame 12 September 1997 to 12 September 2008 at USGS gage.

Water Year	Date	Gage Height (ft)	Stream Flow (cfs)
1998	21 Mar 1998	9.73	2,670
1999	16 Sep 1999	9.31	2,320
2000	14 Jul 2000	9.77	2,710
2001	11 Aug 2001	12.56	5,880
2002	19 Jun 2002	8.33	1,610
2003	23 Sep 2003	11.40	4,380
2004	11 Dec 2003	11.31	4,280
2005	14 Jan 2005	10.56	3,460
2006	26 Jun 2006	13.72	7,660
2007	16 Nov 2006	11.44	4,430
2008	6 Sep 2008	16.26	12,600

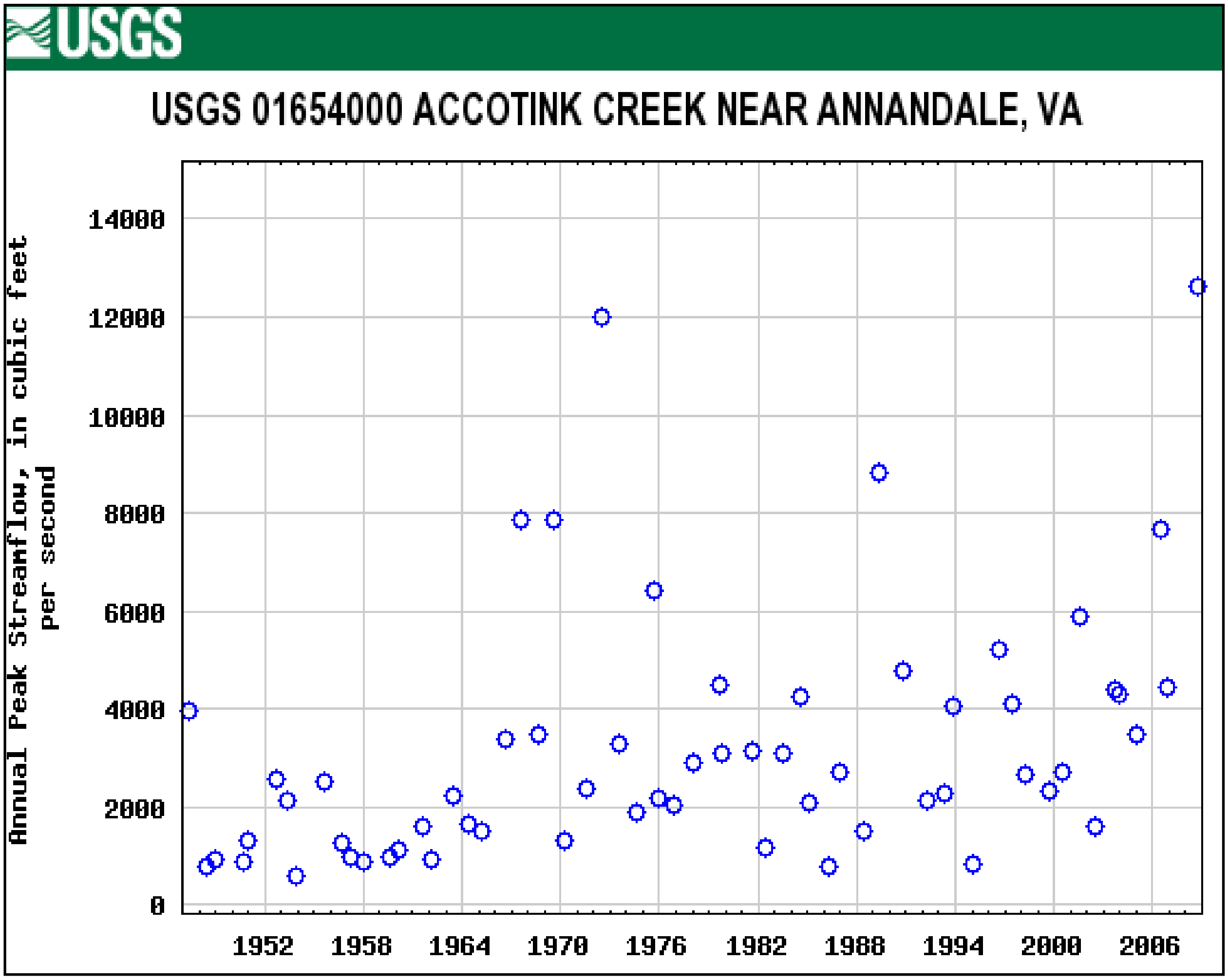

Figure 11. Flow data from Sheladia report.

PROJECT PERFORMANCE 1997-2008

General Overview. During the time period September 1997 to March 2008 the project has been photographed and reviewed in the field several times (February 1998, June 1998, May 2000, May 2006, January 2008, and June 2008). It has performed as designed, and has not needed repair. Most structures look similar to the as-built condition, except that bendway weirs 4 and 5 have lost some crest height due to turbulence within the deep scour hole at the face of the cliff where they are located. In most cases the LPSTP has collected fine deposition and has become vegetated to some degree. Indicators show that all sections of the project are stable, with no visible erosion or instability within the project, or immediately upstream or downstream. The banks and overbank areas both upstream and downstream of the bridge are stable and have become well vegetated.

Problems not Solved by Project. The project did not eliminate or have a discernable effect on the large cobble-gravel bar upstream of the bridge. This bar is caused by reduced flow velocities due to the undersized bridge opening. While the approach flow angles to the bridge and flow characteristics through the bridge have been improved, the problem of debris collecting on the

upstream side of the bridge has not been completely eliminated. This problem is also an effect of the undersized bridge opening and low bridge girders. Backwater effects from the bridge and flooding of overbank areas is a function of both the undersized bridge opening and the highway approaches to the bridge acting as a dam to creek flows.

Function and Performance of Specific Structures. The left bank LPSTP has effectively protected the left bank from erosion along the entire length of the LPSTP. While some self-adjustment (launching) of LPSTP stone (on the river side) has occurred, that was expected and has not become excessive as the present crest height of the LPSTP matches the original as-built crest height.

Floodplain Formation. An interesting and successful aspect of this project is the amount of deposition that has occurred on top of, and landward of, the upper 125 ft of the LPSTP, where the false bank line was constructed (Figures 12-14). The channel is depositing sediment and forming a floodplain in the left overbank. In some sections the deposition has built up 4 ft over the LPSTP. This floodplain formation is an unusual feature of this project. One contributing factor is a plentiful supply of sediment. The second factor is the top elevation of the LPSTP (as built) in the false bank line. From experience on other projects, it is known that if the LPSTP is constructed either too high or too low, a floodplain will not form. If the LPSTP is constructed too high, the overbank area is only accessed rarely by the channel flows (similar to a terrace). If the LPSTP is constructed too low, it will be overtopped frequently with high-velocity flows. These will scour sediment from the low overbank area (rather than depositing it). The LPSTP may fail if it is not designed to withstand frequent impinging flows. The height and configuration of the LPSTP false bank line worked well in this situation to “nudge” the channel into building its own floodplain. It is an excellent example of a design that works with the natural tendency of the channel. Further investigation into the factors that caused success here (hydrology, sediment loads, and LPSTP design) would be useful. For instance, the flashiness of the discharge regime in this urban watershed may increase the range of “successful” LPSTP elevations for floodplain formation.

The LPSTP on the left bank extends downstream so far as to negate the “kicker” effects of the two existing bank scallops located upstream and downstream of bendway weir 5 (Figure 15). The effects of these scallops can be seen clearly in the shape of the midchannel cobble bar in the pre-project aerial photograph (see Figure 2). This section of LPSTP also functions to align left of center stream flow.

The right bank LPSTP has effectively provided protection for the right bank, the seven mature trees along the right bank, and the right bridge abutment (Figure 16). The thalweg is usually impinging into the upper section of the LPSTP, and then runs parallel with the LPSTP providing excellent current alignment into Panther Bridge. Even with the stream forces working on this for 10 years, only relatively minor self-adjusting has occurred. The use of stone toe in this section eliminated the need to grade the right bank, and allowed mature riparian vegetation to be saved. No significant retreat of the upper bank has occurred.

Figure 12. Mid-project from cliff looking at LPSTP and weirs 2 and 3, 1 February 1998 (5 months after construction). Note: low area and water landward of LPSTP.

Figure 13. Looking downstream at new deposition landward of LPSTP at weir 3, 8 June 1998 (9 months after construction).

Figure 14. Looking downstream at weirs 2 and 3, 17 May 2000 (2.7 years after construction).

Figure 15. Looking downstream at left bank, 1 May 2006 (8.75 years after construction) 4 ft of deposition on LPSTP with some robust vegetation.

(a) (b)

Figure 16. Right descending bank upstream of Panther Bridge, 1 May 2006 (8.75 years after construction). PSTP, mostly hidden, still protecting trees a decade after installation. (a) Looking upstream. (b) Looking downstream.

The bendway weirs have performed as expected. In this project, during high-flow events, velocities are reduced in the weir field, and the thalweg has moved to an alignment at the stream ends of the weirs. In this project, the three upstream bendway weirs (Weirs 1, 2, and 3) were constructed approximately 10 ft too long. This has led to some minor scour of the point bar on the opposite bank (the right bank) since the thalwag has been shifted further to the right than desired. This project was one of the first applications of bendway weirs on a smaller stream. To determine bendway weir length, the required thalweg alignment is determined and laid out on the plan sheet, and the bendway weirs are drawn so that the stream ends of the weirs are located just short of the thalweg location. The additional bendway weir length used in this project has not hindered overall project function greatly. The weir field contains a diversity of depths, velocities, and substrates not found in other sections of the project. The slower velocities allow sediments (sands, silts, gravels and cobbles) to deposit along with leaf litter and detritus (Figure 17).

Due to the size of stone used, the bendways vary above and below low-flow water-surface elevation, creating mini-blockages and concentrated velocity streams (Figures 18 and 19). In these areas air is entrained into the water column, and turbulence from flow (eddy fences, vortices, return currents, etc.) results in enough fluid movement and modulation to provide “hydraulic cover” for fish.

Figure 17. Within weir field bed substrate consists of a diverse mix of gravel, cobble, sand, and leaf litter, 14 January 2008 (10 years after construction).

Figure 18. Closer view of stream end of bendway weir 3, 14 January 2008 (10 years after construction). In addition to surface disturbance and aeration there is great diversity and complexity of velocities, depths, and subsubstrate (sand patches within cobble-gravel) within weir field.

Figure 19. Close-up of crest of bendway weir 2, 14 January 2008 (10 years after construction). Mini plunge pool, aeration, structure, hydraulic cover and solid stable substrate for benthic invertebrates.

CONCLUSIONS: This project demonstrates the successful application of two low-cost techniques (stone toe and bendway weirs) to protect infrastructure, prevent erosion, and modify channel alignment in a highly urbanized watershed. The project has performed well for over 10 years (Figures 20 and 21), through multiple high flow events and one extreme event (September 2008). No maintenance has been required. The project has been effective, economical, and environmentally sensitive. The combination of a direct technique (stone toe) and an indirect technique (bendway weirs) has worked well. The techniques were adapted to site conditions to minimize environmental impacts. The ongoing formation of a floodplain in the left overbank is an unusual and successful feature. The project has delivered long-term protection for an important infrastructure component of Garrison Fort Belvoir.

Figure 20. Looking upstream at bendway weirs 1-3 (10 years after project completion, 14 January 2008). Banks are stable.

Figure 21. Looking upstream from Panther Bridge. Both banks are stable (10 years later, 14 January 2008).

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> Derrick, D., and M. M. Jonas. 2010. *Innovative streambank protection in an urban setting: Accotink Creek, Virginia.* Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-VII-10, Vicksburg, MS: U.S. Army Engineer Research and Development Center, *http://chl.erdc.usace.army.mil/chetn*.

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